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December 7, 1994

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William F. Caton
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FEDERAL COMMUNICATIONS COMMISSION
OFFICE OF SECRETARY

Re: Ex Parte Communication
PR Docket No. 93-61
Automatic Vehicle Monitoring

Dear Mr. Caton:

Transmitted herewith is a paper entitled "On the Effect of Bandwidth on the Performance of AVM Systems Operating in the 902-928 MHz ISM Band" prepared at the request of Pinpoint Communications, Inc. The paper was prepared by Dr. Costas N. Georghiades, Associate Professor in the Electrical Engineering Department of Texas A&M University, one of the three "Research Centers of Excellence" recognized by the Intelligent Transportation Society of America.

In his paper, Dr. Georghiades addresses the effects of wider bandwidths (*e.g.* 8-10 MHz) on the performance of wide-area Automatic Vehicle Monitoring systems. Dr. Georghiades finds that:

> wideband systems in the range of 8 to 10 MHz are significantly better able to combat multipath compared to narrowband systems with 1 to 2 MHz. This capability benefits both data detection and location accuracy. Moreover, wideband systems provide a number of location fixes per second which increases as the square of the bandwidth, for the same power.

Dr. Georghiades also notes that:

> The central question is not whether AVM systems *can* be built at smaller bandwidths. Rather, in the severe multipath

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> environments in which AVM systems will operate, can systems capable of providing sufficiently accurate location and adequate capacity for intelligent vehicle highway systems (IVHS) be built if bandwidth is not increased . . .. AVM systems are expected to greatly facilitate implementation of IVHS by providing both messaging and location monitoring capabilities to large numbers of vehicles at a time. To do so, they require large bandwidths.

Please contact the undersigned if there are any questions.

Respectfully submitted,

David E. Hilliard

David E. Hilliard
Counsel for Pinpoint Communications, Inc.

Enclosure
cc: See Attached List

On the Effect of Bandwidth on the Performance of AVM Systems Operating in the 902-928 MHz ISM Band

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Abstract

Much discussion has recently focused on the effects of signaling bandwidth on the operation of Automatic Vehicle Monitoring (AVM) systems. These AVM systems are authorized to operate in the 902-928 MHz ISM band, which is also currently used by the unlicensed Part 15 devices. The band presents significant challenges to the system designer in that it is characterized by interference and multipath, which together preclude a neat mathematical analysis. In this study, we focus on the role of bandwidth in mitigating multipath, which is one of the major impairments in the operation of AVM systems. As demonstrated herein, wideband systems in the range of 8 to 10 MHz are significantly better able to combat multipath compared to narrowband systems with 1 to 2 MHz bandwidth. This capability benefits both data detection and location accuracy. Moreover, wideband systems provide a number of location fixes per second which increases as the square of the bandwidth, for the same power.

I. INTRODUCTION

The current regulatory proceeding concerning the continued operation of automatic vehicle monitoring (AVM) systems in the 902-928 MHz band has raised some interesting questions on how much bandwidth is needed for such applications to operate satisfactorily. AVM systems operate in urban environments characterized by severe multipath and interference from unlicensed Part 15 devices in the 902-928 MHz band, and can provide both data communication between vehicles and base stations, and location information in real-time to meet various fleet management and other vehicle location needs. Among other applications, AVM systems are expected to play an important role in the implementation of intelligent vehicle highway systems (IVHS), by potentially providing real-time traffic information, route guidance, and other information to fleet managers, public traffic monitors, public safety offices, and individual drivers. Demand for such services is expected to increase significantly in time, requiring the service provider to be able to handle large numbers of vehicles at a time.

The combination of mobile communication and interference in an urban environment results in a rather hostile channel that is broadly characterized by multipath and interference. In Section II we study the role of bandwidth in mitigating multipath, and in Section III its effects on the location accuracy and number of location fixes per second for AVM systems. Section IV concludes.

II. THE EFFECT OF BANDWIDTH ON DATA DETECTION IN MULTIPATH FADING

Multipath and multipath-induced fading are major sources of performance degradation in mobile data communication systems, and is a result of transmitted signals arriving at the receiving antenna with different amplitudes and delays (and thus phases), having traversed different paths.[1] In order to determine how much bandwidth the system requires, one must specify the smallest delay that a system will be asked to resolve. Experimental data obtained in various urban settings in [2] indicate that significant multipath power is possible over a delay range from a few tens of nanoseconds to a few microseconds. Other results by Schilling in [3] indicate that large amplitude components exist with relative delays less than 100 ns, which means that a wideband system should have a bandwidth in excess of 10 MHz in this case.

[1] An excellent discussion on multipath can be found, for example, in Chapter 7 of Proakis's book [1].

In the absence of a direct path between transmitter and receiver, the amplitude and phase of the received signal in each path are often modeled having Rayleigh and uniform distributions, respectively, which results in a signal with independent, zero-mean Gaussian processes for the in-phase and quadrature components. The spectral-density of the received Gaussian process, which characterizes the memory and bandwidth of the received signal, is a function of the Doppler frequency shift, which in turn is a function of the relative velocity between transmitter and receiver. Typical Doppler frequency shifts, depending on vehicle speed, are in the range of 10-100 Hz, resulting in a relatively slowly varying process (compared to the signaling rate) that can be tracked in time. For a description of multipath, one must determine *how many* significant (i.e. having appreciable energy) delayed versions of the transmitted signal are received, and *what their delays* are. Both the number of significant multipath components and their corresponding delays are random variables whose realizations depend on the spatial position of the transmitter and receiver and their surroundings (buildings, bridges, etc.). It is easily determined that a one foot difference between two traversed paths results in a 1 ns (10^{-9} seconds) time-delay between them.

In "narrowband" direct-sequence spread-spectrum and CDMA systems, it is possible that a number of signals arriving having traversed different paths may have delays that are within a chip interval. In this case, the receiver cannot resolve these multipath components, resulting in diffuse (Rayleigh) fading, perhaps with a small specular component. On the other hand, in "wideband" (small chip duration) direct-sequence spread-spectrum and "wideband" CDMA systems the various multipath components arrive with delays greater than a chip interval, allowing the receiver to resolve them. This results in a channel with a strong Rician component and a small diffuse component. In this case, the receiver designer has the option of building a simple correlation receiver which is able to capture the energy in a single (strong) component while rejecting other components as interference, or to built a more complicated (but better performing) RAKE receiver [4] which combines the energies of a number of resolved components to make symbol decisions.

In either case, it is clear that performance-wise, the system is better off operating in wideband mode. Quantitative results that support the above arguments can be found in [5]. These results also indicate that wideband systems are less susceptible to Doppler spread, and in the limit of large chip rates, the fading in the channel diminishes resulting in a performance approaching that in an additive Gaussian channel. Further results in [5, 3] indicate that at high chip rates good performance can be obtained with simple correlation receivers, avoiding the need for the more complex RAKE receivers.

In recent work [6] on the same question of how bandwidth affects performance in a multipath environment, an assumption of a two-ray multipath channel is made, with a delay that varies between 5 and 7 μs for urban environments. This model was used to obtain simulation results for the proposed IS-95 CDMA cellular radio standard (with interleaving, rate 1/2 convolutional coding, and a RAKE receiver, but apparently without near-far effects) at a 1.25 MHz bandwidth and at an SNR of 10 dB. The obtained error-rates were around 10^{-2}. Based on these results, the authors conclude that relatively "narrowband" AVM systems, i.e. 1.25 MHz, are *feasible* in a multipath environment. Although this conclusion may be valid based on the assumed model, there are a number of weaknesses in it: a) experimental results (see [2, 3]) do not support a two-ray model as being realistic; b) the model assumes that each of the two paths is Rayleigh faded, regardless of the bandwidth, which is not valid. It is known that as bandwidth increases, the channel appear to behave more like a Gaussian channel [5]; c) the central assumption of the model, that delay is in the range of 5-7 μs, is overly simplistic (see [2, 3] and the discussion above which indicate that a delay of the order of 100 ns is more realistic); d) an error-rate of 10^{-2} may be acceptable for voice communication, but it is too large for data communication (such as in AVM systems). To achieve the smaller error-rates required by AVM systems, one must either increase the signaling bandwidth, or suffer a reduction in data-rate. Recent work in [7] which compared the capacity efficiency of narrowband (1.25 MHz) and wideband (10 MHz) CDMA systems in the presence of multipath, the authors conclude that *"...Wideband systems (10 MHz bandwidth) achieve greater efficiencies in terms of capacity per MHz."*

The central question is not whether AVM systems *can* be built at smaller bandwidths. Rather, in the severe multipath environments in which AVM systems will operate, can systems capable of providing sufficiently accurate location and adequate capacity for intelligent vehicle highway systems (IVHS) be built if bandwidth is not increased (which was not really addressed in [6]). AVM systems are expected to greatly facilitate implementation of IVHS by providing both messaging and location monitoring capabilities to large numbers of vehicles at a time. To do so, they require large bandwidths.

III. The Effect of Bandwidth in Estimating Location

In hyperbolic multilateration AVM systems, vehicle location is obtained by measuring the arrival time of a signal transmitted by the mobile at a number of spatially distributed base stations, followed by triangulation. The ultimate measure of performance for the system is in terms of the error in locating a vehicle in three-dimensional space. However, as the estimation of actual vehicle location (through triangulation) involves nonlinear processing of a number of delay estimates, it is analytically intractable to analyze its performance directly. In most cases, thus, one resorts to studying the performance of the delay estimator, with the intuitive expectation that the better the delay estimates are, the better the final vehicle location estimate will be after triangulation. This, in fact is the case, as indicated by simulation results (see for example [8, 9]). A measure of the quality of the delay estimate is easily obtained in terms of the Cramer-Rao bound (see for example Van Trees [10] for a general exposition).

A delay estimate can be obtained by transmitting an appropriate sequence (i.e. one with good autocorrelation properties, such as an m-sequence or a Gold sequence). At the receiver, a maximum-likelihood (ML) estimator correlates a replica of the transmitted sequence with the received data and detects the time when the correlation peaks (or, in practice, when it exceeds some threshold). It declares that the sequence was detected at the time when the correlation is largest. If we let σ_τ^2 be the variance of the estimation error, the Cramer-Rao bound yields (see for example [11, 12])

$$\sigma_\tau^2 \geq \frac{1}{4\pi^2 \frac{2E}{N_0} N B^2} \tag{1}$$

where

$$B^2 = \int_{-\infty}^{\infty} f^2 |P(f)|^2 df$$

and

- N is the number of symbols (pulses) in the transmitted sequence
- E is the energy in one of the transmitted symbols
- $N_0/2$ is the two-sided spectral density of the (assumed) additive Gaussian noise
- and $P(f)$ is the Fourier transform of the transmitted unit-energy pulse $p(t)$:

$$\int_{-\infty}^{\infty} p^2(t)dt = \int_{-\infty}^{\infty} |P(f)|^2 df = 1.$$

B is the root-mean-square (rms) signal bandwidth, also known as the Gabor bandwidth, and $2E/N_0$ is the signal-to-noise ratio (SNR). Let us specialize (1) to the case of the popular and often practically used class of bandlimited raised-cosine pulses. If the chip rate is $1/T_c$, then

$$|P(f)|^2 = \begin{cases} T_c & 0 \leq |f| \leq (1-\beta)/2T_c \\ \frac{T_c}{2}\left[1 - \sin[\pi T_c(|f| - 1/2T_c)/\beta]\right] & (1-\beta)/2T_c \leq |f| \leq (1+\beta)/2T_c, \end{cases}$$

where $0 \leq \beta \leq 1$ is the *roloff-factor* which determines the excess bandwidth ($\beta = 0.25$ is a practical value often used). The bandwidth, W, of raised-cosine pulses relates to the chip rate in accordance with

$$W = \frac{(1+\beta)}{2T_c}.$$

For this class of pulses, (1) becomes

$$\sigma_\tau^2 \geq \frac{1}{A\frac{2E}{N_0}NW^2} \tag{2}$$

where A is some constant determined by the roloff-factor and given by

$$A = \frac{4[\pi^2/3 + \beta^2(\pi^2 - 8)]}{(1+\beta)^2} \geq 5.$$

The bound in (2) is valid for all parameter values, and is known to be tight for even small SNR's (more than about 3 dB [13]), which are significantly smaller than those expected to be present in practical systems. Equation (2) shows clearly the quadratic improvement in location accuracy as the signal bandwidth is increased, for a fixed SNR.

Although the above conclusions about the desirability of wider bandwidths were based on a white Gaussian noise channel, we expect that they will be strengthened for the mobile multipath channel. In this case, location accuracy will depend not only on improved timing performance, but even more so on the ability to resolve multipath components. Wideband AVM systems that can effectively resolve multipath can essentially remove its effects and thus provide significantly improved location accuracy.

Let us now study the effects of bandwidth on the number of location fixes per second. For this comparison, let us fix the signal power, P, which relates to the energy E according to

$$E = PT_c = \frac{(1+\beta)}{2W}P.$$

Substituting in (2), we obtain

$$\sigma_r^2 \geq \frac{1}{\frac{A(1+\beta)}{2}\frac{2P}{N_0}NW}. \tag{3}$$

The number of location fixes per second, r, is given by

$$r = \frac{1}{NT_c} = \frac{2W}{(1+\beta)N},$$

which when substituted in (3) gives

$$\sigma_r^2 \geq \frac{r}{A\frac{2P}{N_0}W^2}. \tag{4}$$

Equation (4) shows that for a fixed mean-square error performance and a fixed power, there is a trade-off between bandwidth and the location rate. Thus, if C is the desired mean-squared error, we have (using the bound as an estimate of performance)

$$C = \frac{r}{A\frac{2P}{N_0}W^2}.$$

Solving for r, we obtain

$$r = A\frac{2P}{N_0}CW^2,$$

which indicates a *quadratic* increase in the location rate with bandwidth, for the *same power and mean-square error performance.* It can be easily verified that if the energy E is fixed instead of power, the location capacity increases as the third power of bandwidth.

Clearly, higher bandwidth could be used to improve not only mean-square error performance, but also to quadratically increase the rate at which position estimates can be obtained for the same power.

There is also an indirect way in which a wider bandwidth can improve location capacity. As discussed in Section II, the bit-error-rate performance of AVM systems improves with increased bandwidth by better overcoming multipath. This improved performance can result in an increased location capacity since it will reduce the number of times base station polling transmissions must be made when errors occur, so that mobiles do not respond to the poll.

IV. Conclusion

We have looked at the effect of bandwidth on the performance of systems operating in the 902-928 MHz band in the presence of multipath. It appears that a larger bandwidth, in the range of 8 to 10 MHz, will:

- allow AVM system designers to design systems that substantially better and at a smaller complexity combat the effects of multipath
- significantly improve the location accuracy and the rate of location fixes for AVM systems.

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Born in Cyprus, February 6, 1955, married, two children.

Research Interests

Optimum receiver design, optical communication, joint synchronization and detection algorithms, coded-modulation, spread-spectrum, and magnetic recording systems.

Education

- *1983-1985 :* Washington University, DSc., Electrical Engineering.
- *1981-1983:* Washington University, MS, Electrical Engineering.
- *1976-1980 :* American University of Beirut, BE, Electrical Engineering (with distinction).

Experience

- *Sept. 1991- :* Associate Professor, Electrical Engineering Dept., Texas A&M University.
- *Sept. 1985-1991:* Assistant Professor, Electrical Engineering Dept., Texas A&M University.
- *Summer 1985:* Instructor, Electrical Engineering Dept., Washington University.
- *1980-1981:* Field engineer, Compagnie Generale de Radiologie, Beirut, Lebanon.

Affiliations

Senior member of IEEE, Professional Engineer in Texas, member Sigma Xi and Eta Kappa Nu, member of ARRL.

Professional Activities

- Associate Editor for Communications, *IEEE Transactions on Information Theory*, 1994-.
- Guest Editor, *IEEE Journal on Selected Areas in Communications* (J-SAC)
- Editor, *IEEE Transactions on Communications*, 1987-.
- Publications Editor, *IEEE Transactions on Information Theory*, 1989-1992.

- Local Arrangements Chairman, *1993 International Symposium on Information Theory* (ISIT), San Antonio, Texas.
- Deputy-Chairman, *Communication Theory Mini Conference* (CTMC), Houston, Texas, November 1993.
- Technical Committee Representative of Communication Theory Committee to Globecom '93.
- Co-organizer of the *Second Texas Systems Day,* College Station, Texas, October 1988.
- Session organizer and chair in a number of conferences.
- Session organizer, *Eighth Texas Systems Day,* College Station, Texas, November 1994.

Invited Talks

- *Synchronization for Optical Communication Systems*, at the IEEE Communication Theory Workshop, Florida, April 1987.
- *Sequence Estimation in the Presence of Phase-Errors Via the EM Algorithm,* at the Fourth Texas Systems Day, Austin, Texas, November 10, 1990.
- *Algorithms for Joint Synchronization and Detection*, 1991 Tirrenia International Workshop on Digital Communications, Tirrenia, Italy, September 1991.
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- *On the Application of the EM Algorithm to Sequence Estimation for Degraded Channels,* University of Texas, San Antonio, November 1994.

Short Courses Taught

- *Digital Communications*, Dallas Texas, April 10-12, 1989.
- *Digital Communications and Synchronization* at Bell Northern Research (BNR), Richardson, Texas, April 26, 1990.

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- C.N. Georghiades, "Signaling over High Speed Optical Intersatellite Links," Proceedings of the *Global Telecommunications Conference*, Houston, Texas, November 1993.

- E. Soljanin and C.N. Georghiades, "On Coding in Multi-Track, Multi-Head, Digital Recording Systems," Proceedings of the *Communication Theory Mini Conference*, Houston, Texas, November 1993.

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- C.N. Georghiades, S. Patarasen, E. Soljanin, H. Jardak and W. Wills, "Communications in Intelligent Vehicle Highway Systems: Part I," Research Report 1245-2, Texas Transportation Institute, November 1991.

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- C.N. Georghiades, "Decoding of TCM in the Presence of Random Parameters Via the EM Algorithm," Progress Report for National Science Foundation Grant NCR-9016329, April 1992.
- C.N. Georghiades, "Modulation, Coding and Synchronization for Throughput-Efficient Free-Space Optical Systems," Progress Report to NASA Lewis Research Center for Grant NAG 3-1353, November 1992.

Major Grants

- National Aeronautics and Space Administration, NAG 5-778, $66,922, May 1986-August 1987, (Shu Lin principal Investigator).
- Institute of Electrical and Electronic Engineers, $21,000, September 1, 1989-August 31, 1992.
- Texas Transportation Institute, *A Study of Telecommunication Requirements for Intelligent Vehicle Highway Systems*, $93,500, January 15 to August 31, 1990.
- Texas Transportation Institute, *A Study of Telecommunication Requirements for Intelligent Vehicle Highway Systems*, $70,000 September 1, 1990 to August 31, 1991.
- Texas Transportation Institute, *A Study of Telecommunication Requirements for Intelligent Vehicle Highway Systems*, $28,000 September 1, 1991 to August 31, 1992.
- National Science Foundation, *Decoding of TCM in the Presence of Random Parameters Via the EM Algorithm*, $99,734, May 1991-May 1993.
- National Aeronautics and Space Administration, *Modulation, Coding and Synchronization for Throughput-Efficient Free-Space Optical Systems*, $45,069, June 1, 1992-September 30, 1992.
- Member of Technology Integration Team, TTI IVHS Research Center of Excellence, 1.5 months salary support.
- Applied Physics Laboratory, *Maximum-Likelihood Based Techniques for Sequence Estimation and Tracking*, $25,600.
- National Science Foundation, *Detection, Synchronization, and Coding for Multiple-Head Recording Systems*, $194,626, pending.
- ALCATEL, *Fast Synchronization Techniques for Digital Radio*, $20,000, pending.

Equipment Grants

- DSP equipment donation by Motorola: $52,000 (with J. Livingston)
- National Science Foundation, *Acquisition of Instrumentation and Computational Equipment for the Experimental Laboratory on VLSI High Performance Signal Processing and Communications*, $416,000 (it includes $185,000 in matching funds)(co-PI).

- Hewlett-Packard, *Instrumentation Acquisition for the Electrical Engineering Communications Laboratory*, $93,159, pending.

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- Chairman, Distinguished Speakers Committee, Department of Electrical Engineering, Texas A&M University.
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